Desulfurization of Gasoline

by Jerry E. Berger*

Although gasoline blending streams exhibit widely varying sulfur concentrations, significant quantities of low-sulfur motor gasoline cannot be manufactured by reallocation of existing components without substantial sacrifices in the useful properties of the remaining fuels having normal sulfur levels. To meet the anticipated demand for low-sulfur unleaded gasoline which may be required for catalyst-equipped automobiles it will be necessary to install process equipment based on known hydrotreating technology.

The effects which this construction program would exert on the activities, abilities and needs of one petroleum refiner are sketched for two degrees of sulfur removal. The impacts of installing the process facilities which would be necessary are discussed in terms of time requirements, capital needs, and added energy expenditures.
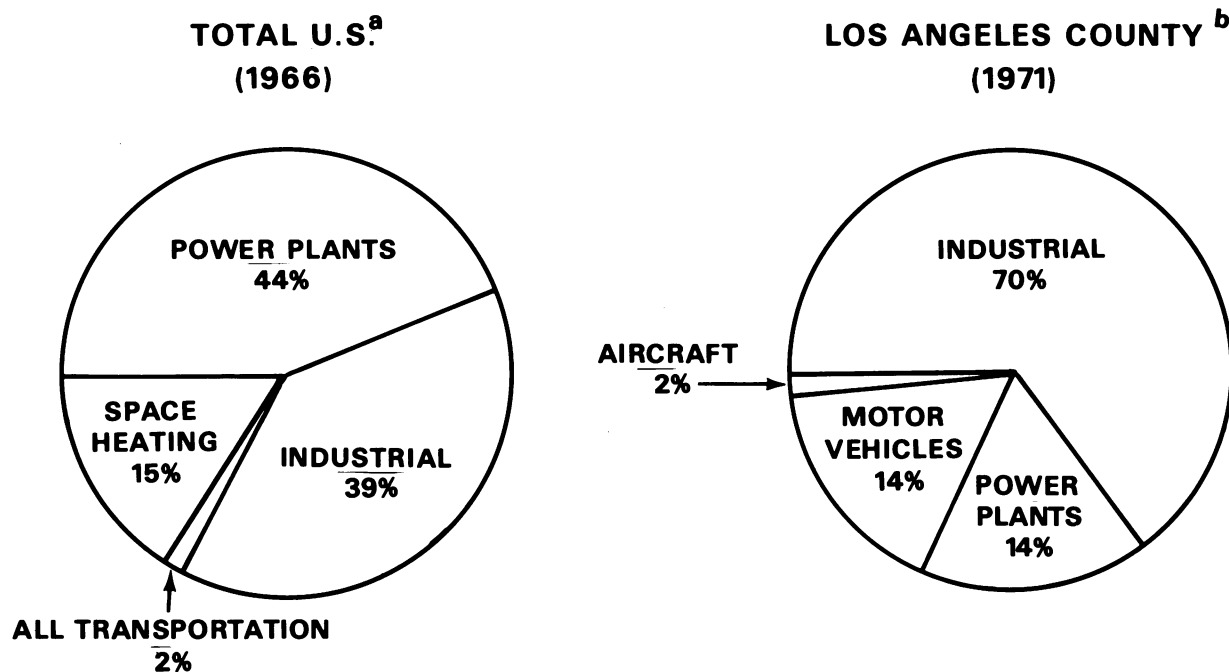
Introduction

Although sulfur dioxide has been a major atmospheric pollutant and although it was one of the first species to command the attention of regulatory bodies, the automobile has not been regarded as a significant contributor to the sulfur dioxide problem. Man's activities account for most emissions of SO_2 to the atmosphere and it is estimated that U.S. emissions of all sulfur oxides have increased by 30% during the last 50 years (1). Despite this increase and despite the growing number of cars on the road, automobiles contribute less than 1% of the total SO_2 burden in the air (2).

Figure 1 shows some of the principal sources of atmospheric sulfur dioxide. For the entire United States, it is estimated that all transportaion activity accounts for about 2% of all SO_2 emissions, while power plants and industrial facilities produce about 44 and 39% respectively, of the SO_2 emissions in the U.S. (3).

The automobile's percentage of total SO_2 emissions varies somewhat from place to place in response to the type of fuel consumed by industrial plants and electrical generators. In Los Angeles County, for example, motor vehicles are estimated to produce 14% of the total SO_2 emissions in that County (4). Among the reasons for this relatively high contribution by vehicles are the following: (1) the vehicle population is high in Los Angeles County, (2) West Coast gasoline tends to have higher-than-normal sulfur levels, and (3) natural gas (instead of coal or residual oil) historically has supplied many power plants and industrial installations and this fact has minimized SO_2 emissions from such sources. The same general profile exists in Houston which is another metropolitan area whose natural gas supply has tended to discourage the use of sulfur-containing coal or residual fuel. In contrast, the New York City area relies to a major extent on coal and residual fuel for power generation and manufacturing; hence automotive sources of SO_2 in that area probably represent only a small fraction of the total atmospheric sulfur oxide.

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TOTAL U.S.[a]
(1966)

POWER PLANTS
44%

SPACE
HEATING
15%

INDUSTRIAL
39%

ALL TRANSPORTATION
2%

LOS ANGELES COUNTY [b]
(1971)

INDUSTRIAL
70%

AIRCRAFT
2%

MOTOR
VEHICLES
14%

POWER
PLANTS
14%

a. National Academy of Sciences—1966.

b. Los Angeles County APCD, 1971.

FIGURE 1. SO₂ emissions by major source.

Under ordinary circumstances, the sulfur dioxide which originates from motor vehicles becomes part of the total atmospheric SO_2 burden and enters the sulfur cycle. Diffuse atmospheric SO_2 is oxidized to SO_3; the time interval for this conversion is generally believed to involve hours or, at most, a few days. Sulfur trioxide quickly acquires water molecules to form sulfuric acid, which is converted to sulfate salts (especially ammonium sulfate); eventually the airborne sulfates precipitate to earth.

Until very recently the contribution of automotive emissions to atmospheric sulfur-containing species was justifiably considered to be minimal. Lately, this situation has changed. The first public warning of this change in attitude occurred in March 1973 when the Ford Motor Company, in testimony before the EPA, revealed that their research had succeeded in identifying sulfuric acid

aerosol in the exhaust of catalyst-equipped vehicles (5). This finding, in itself, was not unexpected; neither was it unduly alarming, since sulfur oxide emissions (as SO_2) from noncatalyst cars eventually are converted in turn to SO_3, H_2SO_4, and finally to inorganic sulfates. The next public report impacting on this question occurred on September 20, 1973, when EPA spokesmen presented a draft interim report on their analysis of CHESS (Community Health and Environmental Surveillance System) data (6). This EPA review for the National Air Quality Criteria Advisory Committee presented epidemiological results which appeared to link airborne sulfates to an increased incidence of respiratory problems. The interim conclusions by the EPA's health experts at that time indicated that low concentrations of airborne sulfates (e.g., 8–10 $\mu g/m^3$) represented the threshold for the onset of adverse

health effects. These findings and tentative conclusions, therefore, raise some serious questions regarding the continued use of sulfur-containing gasoline in a growing population of catalyst-equipped vehicles. These questions do not concern the total amount of sulfate-containing species generated in the atmosphere, since the total amount probably is the same whether or not catalysts are used. What is of concern is the fact that catalyst-equipped cars operating on today's gasolines can produce localized concentrations of sulfate species which are high relative to the usual diffuse atmospheric levels. These localized high concentrations probably will be experienced first in the neighborhood of heavily traveled freeways and in busy city street canyons.

Further insight relevant to these serious questions accrued when EPA Administrator, Russell Train, testified on November 6, 1973, before the Senate Public Works Committee (2). At that time Mr. Train stated that one year's production of catalyst-equipped cars could be tolerated without endangering public health. Subsequent written statements by EPA to the Committee indicated that, according to calculations based on atmospheric models, two years' production of catalyst-equipped cars could produce localized concentrations of airborne sulfates in excess of the 8–10 $\mu g/m^3$ level which has tentatively been judged to be the "safe" level (7).

With this background, I would like to discuss the sulfur-in-gasoline question in the context of a scenario based on the following asumptions.

1. Oxidative catalysts will be introduced on most 1975-model new cars; for at least the next several years the use of these devices on new cars will be widespread. This assumption is based on our belief that alternate means for achieving existing 1976–77 exhaust emission standards are not likely to be successful in time to meet the current time-table.

2. Preliminary CHESS conclusions will not be refuted as additional data accumulate. This assumption is based on our view that the EPA's initial interpretations of CHESS results, although neither final nor unalterable, probably will be generally confirmed with regard to the threat to human health of airborne sulfates.

3. Sulfate "traps" or other devices for eliminating sulfuric acid aerosols from vehicular exhaust will be neither timely nor viable solutions to the problem which may confront us.

4. Because of the foregoing, the EPA may impose regulations governing the sulfur content of unleaded automotive gasoline.

This presentation deals with the implications of this scenario from the viewpoint of one oil company; the opinions expressed are those of Shell Oil only.

Where We Are Today

Sulfur levels in U.S. automotive gasoline have been declining slowly with time. This decline has not been due to the possibility of a catalyst/airborne sulfate dilemma because, as explained earlier, this issue has entered into focus only since late 1973. On the other hand, the needs of the public have been ignored in the past: Some gasoline components have been desulfurized to eliminate objectionable odors and others have been treated to reduce objectionable side effects associated with sulfur-containing gasoline constituents. Probably the greatest reduction in gasoline sulfur levels accompanied the evolution of automobile engines during the 1950's and 1960's toward more efficient, high compression-ratio powerplants. These engines exhibited an appetite for fuels of higher octane number and this appetite required greater proportions of chemically altered or synthesized fuel components which, because of the nature of the chemical transformations involved, are low in sulfur content.

Table 1 contains data describing the average sulfur contents of regular-grade and premium-grade fuels marketed in the U.S. during recent years (8, 9). Note, in Table 1, that the average sulfur content in regular-

Table 1. Recent average sulfur levels of U.S. motor gasolines. [a]

	S, wt-%	
	Regular grade	Premium grade
Winter, 1971–1972	0.044	0.026
Summer, 1972	0.042	0.026
Winter, 1972–1973	0.038	0.023
Summer, 1973	0.040	0.026

[a] Data of Bureau of Mines (8,9).

Table 2. Recent average sulfur levels of U.S. motor gasolines by region (summer, 1973). [a]

Region	S, wt-%	
	Regular grade	Premium grade
Mid-Atlantic Coast	0.037	0.024
Southeast	0.037	0.026
Lower Mississippi Valley	0.044	0.034
Central Mississippi Valey	0.039	0.021
Pacific Northwest	0.017	0.008
Southern California	0.046	0.034
Southern Californa (winter 1972–3)	0.069	0.042
Southern Californa (winter 1971–2)	0.105	0.039

[a] Data of Bureau of Mines (8,9).

grade gasoline is about 0.04 wt-% (400 ppm). For premium-grade gasolines, the average sulfur level is about 0.025 wt-% (250 ppm). Sulfur levels vary from place to place and between manufacturers; these differences reflect the type of crude oil processed and the nature of the gasoline processing equipment in existence at a particular refinery. Historically, southern California gasolines have shown higher-than-average sulfur levels due to the high-sulfur crude oil in this region. Additional data describing average sulfur levels in U.S. gasolines for various regions are contained in Table 2; note that southern California, in the past, has been characterized by relatively high sulfur levels in gasoline (8, 9).

A modern gasoline is a blend of several components and each component has attributes which make its inclusion in motor fuel desirable. A typical gasoline composition is described in Table 3, and typical sulfur levels for each component also are shown. These values are merely representative and it should be emphasized that both the gasoline composition and the sulfur levels of individual components may vary up and down from refinery to refinery depending on the availability of equipment and the nature of the raw material employed by different manufacturers.

Butane is naturally low in sulfur content. Hydrocrackate, alkylate, and reformate streams are low in sulfur content due to treatment of feedstocks to remove sulfur and nitrogen compounds. This treatment is required for efficient subsequent refinery processing. The two catalytically cracked streams are conspicuous because of their high sulfur levels and because collectively these two base blending components account for about 30% of the volume of the gasoline pool. The schematic gasoline composition shown in Table 3 will produce a motor fuel having 350 ppm sulfur of which more than 95% percent is derived from the catalytically cracked streams. This suggests that catalytically cracked components are the logical place to apply desulfurization processing.

In Table 4 some generalizations are listed which describe the merits of the principal gasoline blending stocks. Your attention is drawn to the catalytically cracked streams which are important components of the gasoline barrel because they represent a large volume, they are economical in cost and they exhibit good octane properties. Hence anything we do to the catalytically cracked streams must recognize these valuable properties. It would not be reasonable, for example, to discontinue using these blending stocks in gasoline because of the large loss in gasoline supply which such a move would entail.

Other points deserving comment under this heading have to do with the level of sulfur found in common crude oils and with the distribution of sulfur-containing species in the crude petroleum sources.

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Table 3. Typical sulfur levels of major gasoline blending components.

	Sulfur, ppm	Amount of component in gasoline blend, vol-%
Butane	5	9
Straight run	100	14
Light catalytically cracked	800	18
Heavy catalytically cracked	1,500	13
Hydrocracked	2	6
Alkylate	5	10
Reformate	1	30
Totals	350	100

Table 4. Characteristics of gasoline blending stocks.

Component	Remarks
Butane	Cold-startability; good front-end octane
Straight run	Low-cost component
Catalytically cracked	Large-volume component; relatively inexpensive; good octane quality
Hydrocracked	Good octane; expensive; low volume
Alkylate	Excellent octane quality; expensive
Reformate	Good fuel-economy; expensive; high-volume component

Table 5. Sulfur levels of selected crudes.

Location and field	Typical sulfur level, wt-%
California, Wilmington	1.3
Louisiana, various offshore fields	0.1–0.3
Oklahoma, Cushing	0.2
Texas, Conroe	<0.1
Lybia, various	0.2–0.6
Iraq, Kirkuk	1.9
Kuwait, Burgan	2.6
Saudi Arabia, various	1.5–3.0
Venezuela, Lagunillas	2.2

[a] Data of McKinney (11).

As might be expected, available petroleum supplies vary widely in sulfur content. Although the average sulfur content of American crude oil probably is below 1%, values range from near zero to very high levels. Perhaps the highest sulfur content of

Table 6. Sulfur levels in unleaded gasoline.

Sample source and date	Sulfur, ppm (wt)[a]
Storage tank A–57, Dec. 6, 1971	22
Storage tank A–57, Dec. 11, 1971	46
Storage tank, Cape Girardeau, Dec. 29, 1971	130
Storage tank A–57, Jan. 4, 1972	83
Storage tank, Toledo, Jan. 5, 1972	52
Storage tank, Harristown, Jan. 5, 1972	38

[a] Sulfur determinations by Dohrmann microcoulometric method.

any U.S. crude is that of Rozel Point, Utah, where a "seep" of inconsequential production on the northeast shore of the Great Salt Lake has an exceptionally high value of 14% sulfur (10). Table 5 illustrates some other typical sulfur levels of crude petroleum (11). No attempt has been made to make this list exhaustive. It is apparent, however, that the Middle East crudes, which are major sources of imported oil, generally have relatively higher sulfur levels than the raw materials we have processed historically.

Although high-sulfur crudes will mean increased sulfur levels in gasolines derived from these raw materials, the gasoline sulfur situation is not as bad as it might seem since sulfur-containing species tend to be high molecular weight compounds which are concentrated in the heavier and residual fuels. Obviously this is a mixed blessing.

The distribution of sulfur-containing components in untreated distillate is shown in Figure 2 (10). Note that sulfur impurities tend to be concentrated in the heavier fractions during crude oil distillation. This figure refers only to the untreated distillates (the so-called "straight-run" fractions); additional processing of a chemical nature such as reforming or alkylation will, as indicated earlier, reduce sulfur contents to lower levels.

Shell-of-the-Future Experience

In the autumn of 1970, Shell introduced an unleaded gasoline to much of our nationwide distribution and marketing system.
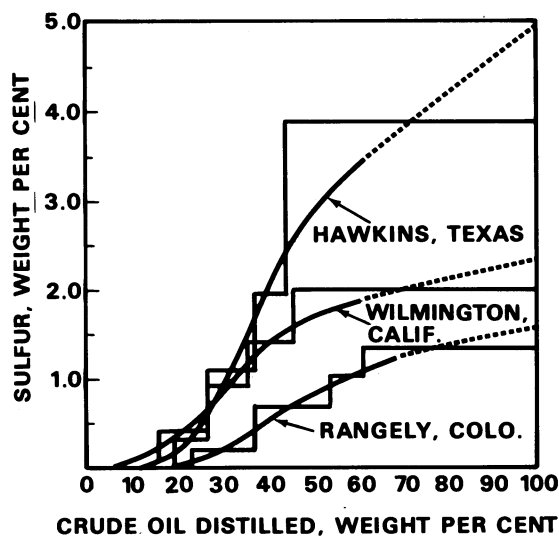
FIGURE 2. Distribution of sulfur in crude oil by boiling range (10).

This product remained on the market until the spring of 1972 when it was withdrawn. In order to maintain acceptable octane quality in the absence of lead anti-knock additives, it was necessary to blend this product using relatively large amounts of hydrocarbon streams having high octane levels. Acordingly, this unleaded gasoline contained abnormally large quantities of alkylate and reformate—two components which are high in octane quality and very low in sulfur content (see Tables 3 and 4).

Hence, the unleaded gasoline exhibited low levels of sulfur, on the order of 100 ppm or lower. Table 6 contains data showing sulfur levels of this unleaded gasoline in various random points in the distribution system in late 1971 and early 1972. It should not be inferred from these data that large volumes of low-sulfur unleaded gasolines can be produced in the near future. In the case of our unleaded motor fuel, it was possible to divert high-octane blending stocks to the unleaded fuel because the demand for this gasoline in its year and a half of availability never exceeded 3.3% of our total gasoline production. Under circumstances of such low product demands, diversion of high-octane blending stocks imposed few serious refinery dislocations. Such diversion of blending components would not be possible under conditions of large demand for low-sulfur unleaded gasoline. Supplying large volumes of such gasoline would entail the desulfurization of other gasoline blending components and this step would require construction of new desulfurization facilities.

Desulfurization Technology

The preferred method for removing sulfur-containing species from catalytically cracked gasoline or from cat cracked feedstock falls in the general category of hydrotreating. Hydrotreating processes, of which there are several variations, consist of mixing hydrogen with the material to be treated, subjecting the mixture to the desired high temperatures and pressures, and passing it through a bed of catalyst. The active catalyst material commonly consists of combinations of cobalt and molybdenum, or nickel and molybdenum, or nickel and tungsten. Although catalyst development continues to afford process improvements, it seems fair to state that hydrotreating technology has reached an advanced state. Depending on the nature of the material being hydrotreated and on the desired degree of sulfur removal, operating pressures range up to 3000 psi and operating temperatures range up to 800°F.

Despite the fact that desulfurizing gasoline involves a known, mature technology and despite the fact that a great deal of hydrotreating capacity now exists in our U.S. refineries, it should not be inferred that removing sulfur from gasoline is a matter of merely turning a valve or punching a button. Existing hydrotreating facilities were designed for particular refinery streams where desulfurization has been previously regarded as necessary to achieve other goals; diversion of this equipment to gasoline would produce unacceptable consequences in other fuels or operations. As future crude oil supplies shift toward higher sulfur levels, the diversion of existing desulfurization equipment to gasolines will become even more

unacceptable, since this equipment is committed to helping resolve other environmental problems.

In general, hydrotreating is an environmentally acceptable process. Sulfur-bearing species are converted to hydrogen sulfide, a gas, which is relatively easy to capture by absorbing it in a suitable liquid. An auxiliary processing plant then strips the H_2S from the absorbing liquid and the hydrogen sulfide is ultimately converted to elemental sulfur using known technology.

There are other impacts of desulfurization which deserve brief mention. Hydrotreating processes consume large quantities of hydrogen, a material which is in short supply at many petroleum refineries. Hence, any large-scale installation of hydrotreating capacity probably will require construction of plants to provide the necessary hydrogen. The energy impact of widespread hydrotreating of gasoline components has several aspects of note: Energy is required to operate the hydrotreating facility, additional energy will be required for hydrogen production and for sulfur recovery facilities, and finally the raw material for hydrogen production is a hydrocarbon. Steam reforming is the mainstay of the industry for producing hydrogen; raw materials range from natural gas to liquid hydrocarbons as heavy as furnace oil. Hence, energy is consumed in operating the required plants and in providing raw material for hydrogen production.

The scenario described earlier leads to the conclusion that it may become necessary to desulfurize large quantities catalytically cracked gasoline via hydrotreating. The question then becomes one of deciding how best to accomplish this end.

Figure 3 shows two alternative methods for approaching this goal. In the first case, the entire feedstock stream to the catalytic cracker is hydrotreated to remove sulfur; in the second alternative only the emerging gasoline components are desulfurized. There are advantages and disadvantages for each scheme.
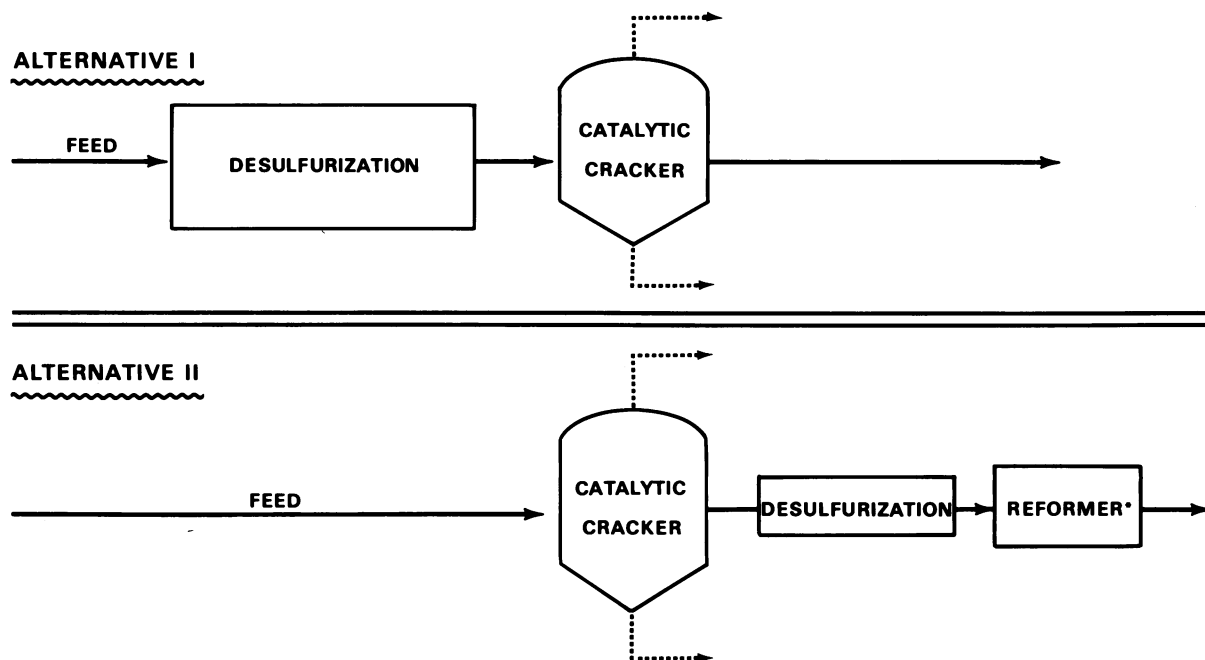
FIGURE 3. Desulfurization of catalytically cracked gasoline.

Since large volumes of products both heavier and lighter than gasoline emerge from a catalytic cracker, Alternative I may result in a greater-than-necessary overall degree of sulfur removal. Certainly much larger desulfurization units will be required to handle this entire feedstock stream: This means a greater investment of time, money and fuel. Parenthetically, it should be noted that many refiners now hydrotreat cat cracker feedstock to remove metals from that stream. Metals removal does not require a high degree of hydrotreating severity and hence a process unit designed for this purpose will have little impact on sulfur concentrations in the stream. On the other hand, light components and heavy components emerging from the cat cracker could be ignored and only the emerging gasoline stream subjected to desulfurization. This case is illustrated in alternative II. Smaller desulfurizers are needed for this case since the volume of product is smaller but there are disadvantages to this approach. Hydrotreating catalytically cracked gasoline results in a substantial loss in octane quality—a penalty of up to ten Research Octane numbers can result from hydrotreating catalytically cracked streams and this could produce an appreciable drop in octane quality for a fully formulated motor gasoline.

To restore this lost octane quality, it appears that additional processing would be required and catalytic reforming seems to be the method of choice. The requirements of alternative II are such that additional reforming plants probably would need to be built; in addition, reforming requires substantial energy input for plant operation. Another energy impact of reforming is related to the by-product low-molecular-weight gases which are produced during the process: This material (methane, ethane, etc.) represents a volume-loss insofar as the gasoline pool is concerned. These by-product volatiles are not suitable for use in motor gasoline but they can be used for other purposes (e.g., chemical feedstocks or refinery fuel). Hence the increased volatiles production results in

a smaller gasoline volume but the energy is not "lost" to society since it can be employed for other applications. It would be necessary, of course, to process additional crude to make up the loss in gasoline yield associated with desulfurization and reforming the catalytically cracked stream.

The Future

It is of interest to speculate about the future which might be imposed by the scenario sketched earlier and to compare the possible future requirements with our historical abilities. In particular, it is germane to inquire as to the construction needs, the capital requirements and the time interval involved in complying with a need for low-sulfur unleaded gasoline.

There are many relevant variables to consider in answering these questions: Among the principal ones are the anticipated demand volume for low-sulfur unleaded gasoline and the timetable which demand-growth imposes. Shell has conducted engineering studies in order to supply answers to the above questions and it seems appropriate to spell out in some detail the premises used in our studies and the base-case upon which comparisons are made.

Shell has eight refineries (three can be considered to be "large" facilities whose daily capacity is about 250,000 barrels each, three are "medium-size" plants with capacities of about 90,000 barels each day, and two are "small" refineries having capacities of about 20,000 barrels per day each); the general approach in this study was to consider each refinery separately and to scrutinize the various gasoline blending streams at each facility to determine what degree of desulfurization might be required for each gasoline component. Each refinery also was considered separately in determining what auxiliary processing equipment might be required to recover lost octane quality. Sulfur levels in individual gasoline components were adjusted from today's value to reflect the changes which we anticipate in future crude

oil compositions. Marginal sulfur-recovery facilities, if any, which might be needed to convert hydrogen sulfide to elemental sulfur are not included in this analysis.

In recent years we have installed a considerable array of processing equipment which has a markedly beneficial effect on the sulfur-in-gasoline dilemma. Indeed, at several locations construction is underway now for facilities which will result in significant reductions in the quantity of sulfur present in cat cracked streams. In general these process modifications are designed to insure compliance with other environmental goals such as stack-gas sulfur dioxide limitations or to cope with higher sulfur crudes. Such facilities are not included in the present estimates: Although they will exert a favorable influence on gasoline sulfur levels, they were designed and built for other reasons and cannot properly be considered to result from concern about tailpipe emissions of sulfates.

Our estimates are also sensitive to the demand growth for low-sulfur unleaded gasoline, since as indicated earlier, small volumes of such a motor fuel can be made by juggling blending components. Our studies indicate that most of our process equipment will need to be operational in 1978 to comply with anticipated demand; given the lead-time requirements for construction, this means that any building program we undertake must begin in 1975.

Adhering to these major premises, refinery-by-refinery estimates were summed for

Table 7. Estimated 1975 capital commitment for one company.

	Capital $ millions
For unleaded gasoline with 100 ppm sulfur:	
Capital	70*
Annual operating cost	12
For unleaded gasoline with 50 ppm sulfur:	
Capital	175*
Annual operating cost	30

* If the inflation characteristic of 1974 continues, capital expenditures may eventually be as high as $80 million and $200 million, respectively (sulfur plants not included).

two cases corresponding to sulfur levels of 50 ppm and 100 ppm; these are summarized in Table 7. For Shell's predictions concerning market demand of low-sulfur unleaded gasoline in 1978, achieving a level of 100 ppm sulfur would require a capital expenditure of about $70 million by 1978. Yearly operating costs associated with this refining equipment are expected to be in the order of $12 million. If, on the other hand, sulfur levels in unleaded gasoline are constrained to 50 ppm, capital and operating costs escalate sharply. For this case, we predict an expenditure of about $175 million would be necessary; annual operating costs are expected to be on the order of $30 million.

This study has not attempted to estimate on a refinery-by-refinery basis the additional fuel consumption due to hydrotreating and auxiilary required processing. However, we do have estimates which are based on a broad "company-as-a-whole" approach and these estimates indicate that our energy requirements for the processing necessary to produce large volumes of gasoline with 50 ppm sulfur are equivalent to 2.5 million barrels of crude per year. This estimate is for refining energy only and does not include the additional crude intake needed to keep gasoline volume constant. This gasoline volume loss, at constant crude intake, is estimated to be 18,000 barels per day for Shell.

Discussion

The estimates made above are abstract ones which assume tacitly that Shell can obtain all the capital needed for all purposes, and that, having obtained it, it can be spent effectively. These assumptions require some further scrutiny and our recent historical business activity is germane to this question.

Capital investments for refining equipment have averaged $75 million per year during` the past ten years; the 10-year high and low values are $123.3 and $32.4 million, respectively. Table 7 indicates that producing unleaded gasoline with sulfur levels reduced to

Table 8. U.S. petroleum industry capital expenditures. [a]

| | Capital expenditures, $ millions | | | | | |
| | Actual | | | Estimated | | |
	1970	1971	1972	1973	1974	1976
Production	5,024	4,924	6,204	6,018	7,222	7,878
Transportation	1,066	991	922	1,586	2,014	1,668
Refining	1,150	1,300	1,066	1,183	1,680	1,754
Marketing	1,392	1,322	1,110	1,110	1,399	1,600
Totals	8,632	8,537	9,302	9,897	12,315	12,900

[a] Data of NPN Fact Book (12).

100 ppm and 50 ppm would require capital commitments of about $70 million and about $175 million, respectively, over the assumed three-year construction period. Our capital investment history for refinery projects indicates we have the capability to cope with this spending level but it must be recognized that other construction projects would have to be curtailed or discontinued. These other construction projects include activities such as energy-conserving measures in our refineries, other environment-related facilities, as well as projects aimed at providing more or cleaner supplies of energy. Our ability to generate the capital required for desulfurization equipment is questionable, unless other business projects are postponed.

Another general facet of the earlier tacit assumptions deals with the construction industry's ability to cope with a sudden increase in demand. The construction industry, like others which endure for any appreciable time, is at equilibrium: Its ability to perform necessary services is approximately equal to the need for such services. A sudden perturbation in demand, for example a demand doubling, probably would exceed the capabilities of the construction industry. Table 8 summarizes some recent history and some short-term projections regarding the capital expenditures of the petroleum industry. Note that refinery construction has entailed about $1 billion in annual investments in the recent past; predictions for the next few years indicate that this may reach about $1.75 billion in constant dollars by

1976. If, indeed, the construction industry is near equilibrium vis-a-vis supply and demand, we question whether it could successfully undertake on short notice a widespread program aimed at desulfurizing gasoline. In addition to that segment of the construction industry devoted to oil refineries and chemical plants, it is of interest to consider briefly the entire heavy construction industry. Our interpretation of recent trends indicates that the electrical power generation industry will require large building programs in the very near future and that this activity is increasing sharply. Refinery construction projects, therefore, may be competing with power-generation projects for the available supply of heavy steel components, especially heavy-wall vessels. It is beyond the scope of this paper to explore this question in detail. It seems likely therefore that some refinery programs would have to be postponed or eliminated during an interim period. This implies some difficult choices will be required to balance energy needs, other pollution-abatement requirements and desulfurization of gasoline.

The availability of materials, capital, of skilled manpower and the adjusting of priorities represent matters of serious concern to us; the choices are not likely to be easy ones and solutions to these problems will not be simple. For these reasons we think that the practice of reducing costs of gasoline processing, including desulfurization, to a cents-per-gallon figure is entirely inappropriate. Such quotients tend to be small numbers due
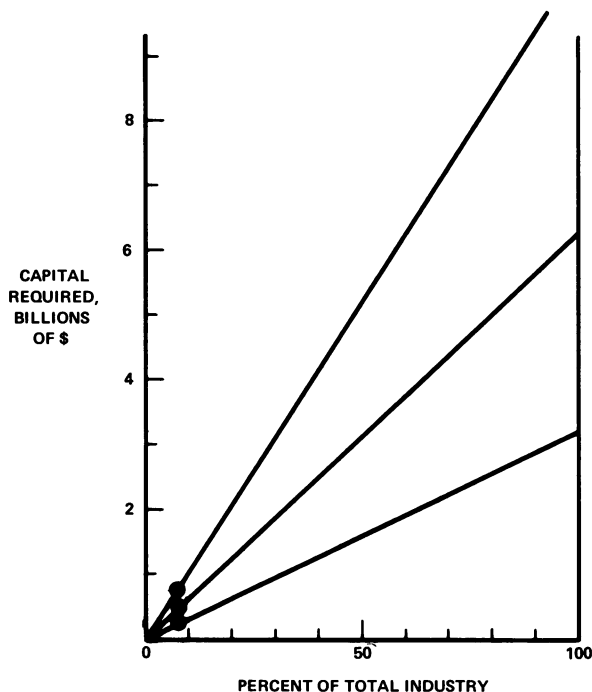
FIGURE 4. Extrapolated estimates of desulfurization costs.

to the large volume of gasoline consumed and the answer obtained leads to a simplistic concept of difficult problems.

Extrapolations of one company's estimates to an industry-wide total also deserve comment. There are 250 petroleum refineries in the U.S.; they come in all sizes, they differ greatly in age, and various raw materials are processed in different ways to satisfy different business strategies. Hence, estimates which are appropriate and accurate for one company may not be applicable to another. Figure 4 illustrates the peril in extrapolating one company's estimate in order to obtain estimates for the entire petroleum industry. For example, Shell's share of the gasoline market historically has been 7 or 8%. Extrapolation of three hypothetical estimates, which in themselves are not widely different, across a span such as the one indicated, produces industry-wide "estimates" covering a wide range of values.

Summary

The above results and discussion can be summarized as follows.

Technology exists for manufacturing gasoline having low sulfur levels,

Anticipated demand for unleaded gasoline is such that additional desulfurization capacity may be required in 1978,

For Shell Oil, capital investments of $70 million or $175 million would be required in order to produce sufficient gasoline in 1978 having 100 ppm or 50 ppm sulfur respectively,

Major unanswered questions include: Will sufficient capital be available? Will sufficient manpower be available to meet a truncated compliance schedule? Can the construction industry cope with the demand?

Additional hydrotreating along with related required processing imposes an additional energy need; gasoline pool volume will shrink somewhat if crude intake is unaltered.

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